# Exploring the Atmosphere of Mars with Remote Observations & Numerical Works Activities in Japan for Martian studies in 'Belgium-Japan partnership' [2017-2018FY]

Y. Kasaba (1), H. Nakagawa (1), H. Sagawa (2), T. Kuroda (3,1), T. Imamura (4), Y. Kasai (3), A. Yamazaki (5), T.M. Sato (5), H. Maezawa (6), M. Taguchi (7), H. Kashimura (8), I. Murata (1), N. Terada (1), T. Sakanoi (1), K. Takami (1), S. Aizawa (1), M. Toyooka (1), T. Akiba (1), N. Yoshida (1), K. Toriumi (1) with A.C. Vandaele (9), S. Aoki (9), S. Robert (9), V. Wilquet (9), A. Mahieux (9), S. Bauduin (9), F. Daerden (9), L. Neary (9), S. Viscardy (9), and P.F. Coheur (10)
(1) Tohoku Univ., (2) Kyoto Sangyo Univ., (3) NICT, (4) Univ. Tokyo, (5) JAXA, (6) Osaka Pref. Univ., (7) Rikkyo Univ., (8) Kobe Univ., (9) IASB, (10) Univ. Libre Brussels

Recent successful explorations of Mars and Venus atmospheres by numerous spacecraft and ground-based telescopes have suggested their active photochemistry and dynamics. Characteristics of spatial and temporal variations of temperature, wind, and atmospheric constituents are essential to understand the photochemistry and dynamics. From April 2017 to March 2019, Japan-Belgium collaboration program, AMAVERO (Exploring the Atmosphere of MArs and VEnus with Remote Observations: A Belgium-Japan partnership) is running. In this project, we study the following aspects. (1) 3D distributions (i.e., spatial variation + vertical profiles) of temperature, wind, and trace gases on Mars, and (2) those at the middle atmosphere (from the cloud top to the upper atmosphere, 60-140 km) of Venus.

These objectives are achieved by collecting observational datasets from Belgium and Japan. Belgian side provides the data taken by European Mars orbiter Mars Express (MEx) and Trace Gas Orbiter (TGO), and Venus Orbiter Venus Express (VEx). From Japan, we provide the data taken by ground-based and spaceborne telescopes with Japanese Venus Orbiter Akatsuki. Moreover, we share tools to analyze the observational datasets, and develop the numerical models of the atmospheres to interpret the observational results. We are executing the following researches based on the exchange of young research staffs, postdocs, and graduate school students: (1) Collaboration of ground-based observations by ALMA sub-mm array, SOFIA IR airborne telescope, and MIRAHI IR heterodyne spectrometer. (for Mars + Venus). (2) Development of Limb retrieval code JACOSPAR for the utilization to ExoMars Trace Gas Orbiter and its test application for $H_2O$ vertical profile derived from Mars Express data. (for Mars: to be appeared in this meeting as Toyooka et al.). (3) Distribution and dynamics of Venusian atmosphere observed by Akatsuki IR imagers. (Venus). (4) The inter-comparison of Venusian and Martian GCMs with cloud and water cycles in different approaches. (for Mars + Venus) (5) Variation of the homopause and atmospheric composition in the upper atmosphere with the comparison between VEX/SOIR + MAVEN + TGO with numerical simulations.

This project was generated from the long-term collaborations between Japan and European groups for Mars and Venus sciences associated with Mars Express (2003-), Venus Express (2005-2015), CrossDrive project (Collaborative Virtual Environments for Mars Science Analysis and Rover Target Planning, 2014-2016), ExoMars TGO (2016-), with groundbased and numerical simulation works. In this meeting, we show the progress and the activities on-going in this project related to Mars Express and ExoMars with the link to MAVEN. In 2018, hot studies are now executed for the Martial global dust storm occurred in summer. Now, we try to extend this project with additional two years in order to cover the full TGO observational activities linked to (1)-(5). Those activities will be extracted to the collaboration of future missions in Japan (e.g. MMX) and Europe (e.g. M4 Venus mission study).
Although this project finishes in March 2019, we try to continue and expand the activities for future.

# Exploring the Atmosphere of Mars with Remote Observations & Numerical Works

A summary

## Activities in Japan for Martian studies in 'Belgium-Japan partnership' [2017-2018FY]


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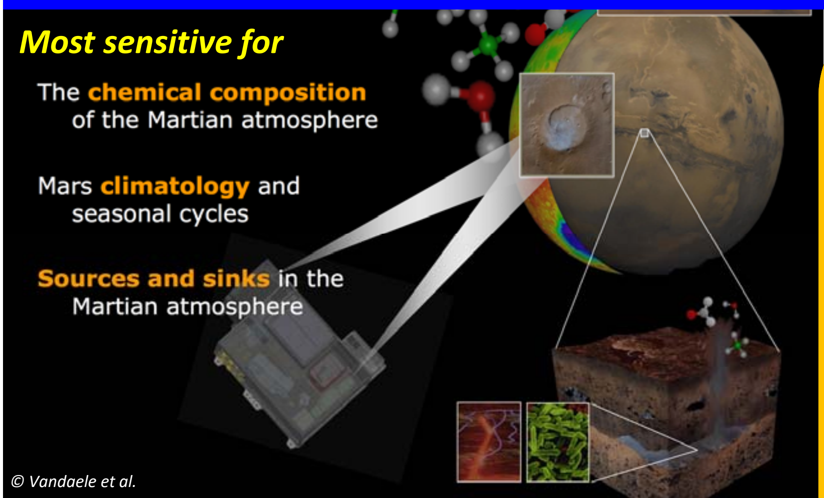
**~ Long recovery road from Nozomi, to the Collaboration with Europe + USA ~**


## ESA ExoMars Trace Gas Orbiter: Full activity from Spring 2018




**"Mars – The Cutting Edge Today"**

Trace Gases: $CH_4$, CO, $O_2$, $O_3$, $H_2O$, HDO, $H_2O_2$, etc.
- 3-D spatial: longitude, latitude, & vertical
- 1-D temporal: (diurnal, seasonal, & inter-annual)
- High resolution (spectral & spatial)

Orbiters & Rovers
- MGS, MRO, Mars Express, Maven, *ExoMars 2016*
- Curiosity, *ExoMars 2018, Mars 2020*

Ground-based
- Keck, NASA-IRTF, VLT
- ALMA, SOFIA

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**NOMAD**
High resolution occultation and nadir spectrometers

*Atmospheric compositio[n] ($CH_4$, $O_3$, trace species, isotopes, dust, clouds, P&T profiles)*

| | | SO | Limb | Nadir |
|---|---|---|---|---|
| **UVIS** (0.20 – 0.65 μm) | λ/Δλ ~ 250 | SO | Limb | Nadir |
| **IR** (2.3 – 3.8 μm) | λ/Δλ ~ **10,000** | | | |
| **IR** (2.3 – 4.3 μm) | λ/Δλ ~ **20,000** | SO | | |

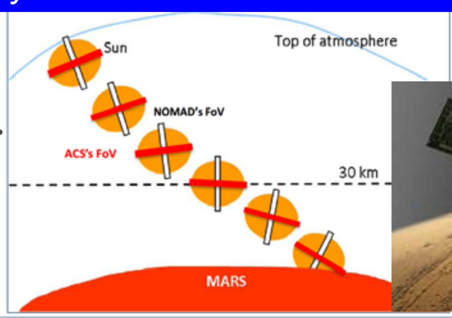
**ACS**
Suite of 3 high-resolution spectrometers

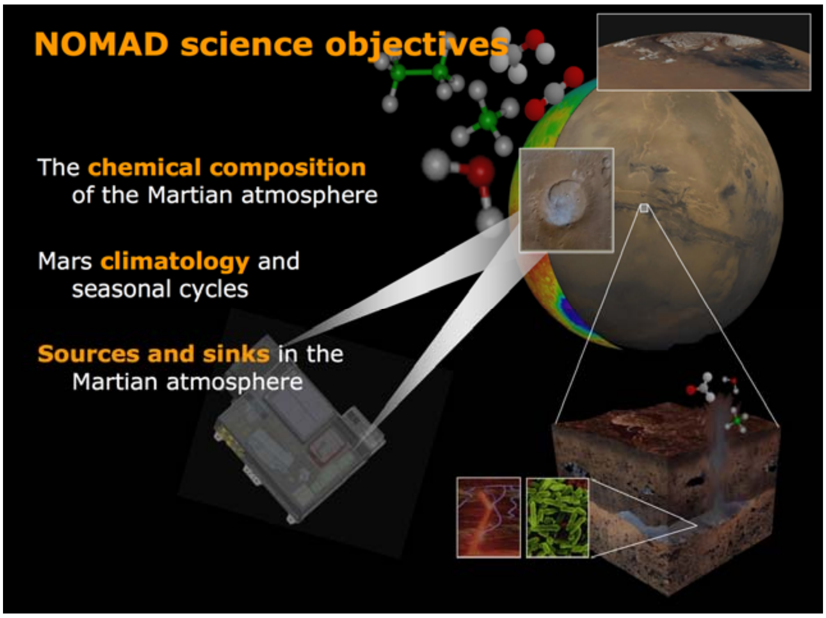
*Atmospheric chemistry, aerosols, surface T, structure*

| | | | | |
|---|---|---|---|---|
| **Near IR** (0.7 – 1.7 μm) | λ/Δλ ~ **20,000** | SO | Limb | Nadir |
| **IR** (Fourier, 2 – 25 μm) | λ/Δλ ~ **4,000** (SO)/500 (N) | SO | | Nadir |
| **Mid IR** (2.2 – 4.5 μm) | λ/Δλ ~ **50,000** | SO | | |

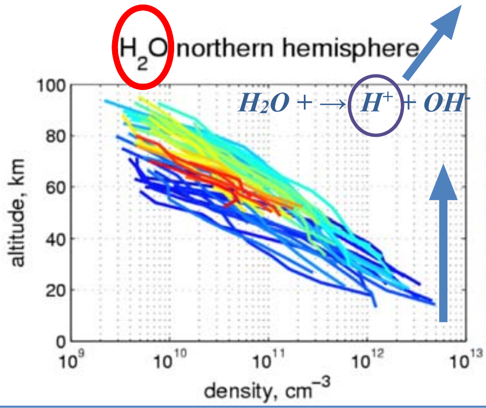
Dawn-Dusk terminators are covered by 'solar occultation' observations.

NIR 2°×0.02°
MIR 0,23°×0,02°
TIR Ø2.5°
(Sun ~0,33°)




## One of the targets: Evaluation of Vertical transportation of Water to the mesosphere




Seasonal variation of the vertical profiles of $H_2O$ for Northern hemisphere, conducted by solar occultation (Fedorova et al., 2018)

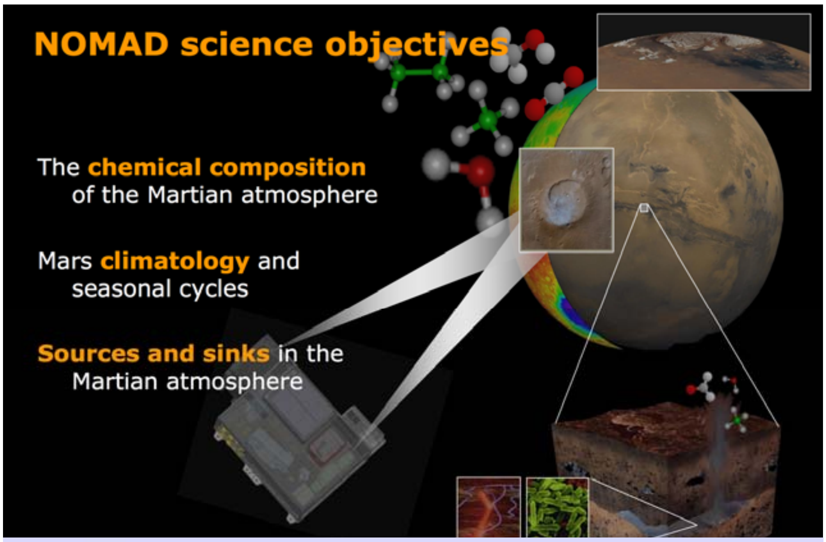
[モデル計算]
この高度で$H_2O$は紫外線(UV)で乖離 → H原子
拡散によって上方へ輸送され、
数週間で宇宙空間へ散逸しうる [Chaffin+, 2017]。

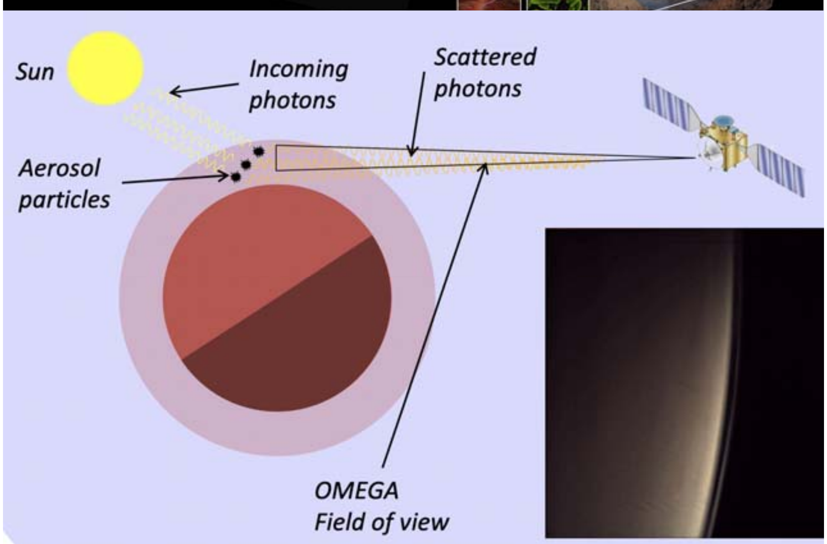
[米MAVEN探査機]
太陽活動度とは独立に惑星空間への
H散逸量が数週間で大変動 [Clarke+, 2017]
--> 下層からの$H_2O$鉛直輸送および熱圏加熱と
その変動は現水素散逸量へ影響しうる。

**Supply / Loss with Surface**
**Vertical connections**
**.... Are critically important !**

Limb observation !
.... CAL & Retrieval are hard ...

**Mahieux et al. (invited)**
**Toyooka et al. (poster)**

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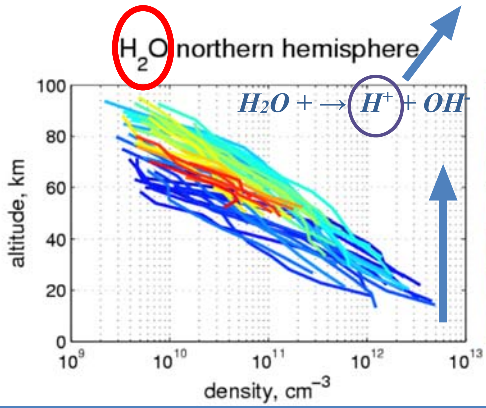


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**Supply / Loss with Surface**
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***Japan-Belgium collaboration in 2017-2018 FY***

# AMAVERO (Exploring the Atmosphere of MArs and VEnus with Remote Observations: A Belgium-Japan partnership)

[supported by JSPS (Japan) + F.R.S .-FNRS (Belgium)]

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| | | |
|---|---|---|
| *Belgium | **Mars orbiter** | ESA **Mars Express (MEx)** |
| | | ESA **ExoMars Trace Gas Orbiter (TGO)** |
| | **Venus Orbiter** | *ESA **Venus Express (VEx)*** |
| * Japan | **Mars orbiter** | NASA **MAVEN** |
| | **Venus Orbiter** | *JAXA **Akatsuki*** |
| | **ground-based / airborne:** | **ALMA, SOFIA** |
| | | **Tohoku Univ 60cm (Haleakala), …** |
| * Both | **Retrieval Tools** | **for Analyses of observational datasets** |
| | **Numerical models** | **for Interpretations [+ Predictions / Ancient studies]** |

*Mars @ JAXA MMX (2024? -)*

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→ Exchange of young research staffs, postdocs, and graduate school students.

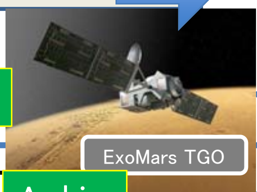
- **Mars Express** (2003-) [with IAPS]
- Venus Express (2005-2015) [with IASB]
- CrossDrive project (Collaborative Virtual Environments for Mars Science Analysis and Rover Target Planning) (2014-2016) [with IAPS, IASB]
- **ExoMars Trace Gas Orbiter** (2017-) [with IAPS, IASB, IKI]
- ground-based / airborne observations [with IAPS, IASB, IKI, MIPT, …]
- numerical simulation works [with IASB, MPI, …]


→ 「水の行方」に代表される現火星の大気変動、特に物質・エネルギーの鉛直輸送機構を解明へ。


| 2018 | 2019 | 2020 – 2021 | 2022 – 2023 |
|---|---|---|---|

**(A) 下層大気の鉛直構造観測**

- JACOSPARの開発・検証 — **Mahieux & Toyooka +**
- MEX等のリム観測データの総合解析
- TGOの太陽掩蔽・リム観測データの総合解析 — Aoki




**(B) 上層大気の鉛直構造観測**

- MAVEN・粒子観測データの総合解析 — Terada +
- MAVEN・紫外観測データの総合解析 — Nakagawa & Yoshida +
- Hisakiの全球ダストストーム時紫外観測データの解析
- TGO・紫外観測データの総合解析

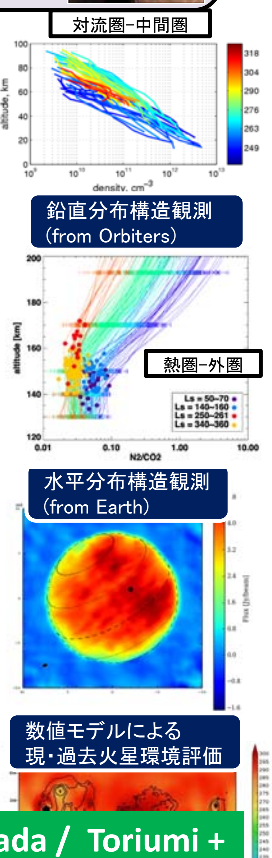
**(C) 全球大気の水平構造観測**

- ALMA 2018観測解析 — **Sagawa & Robert +** — ALMA 2022観測解析
- SOFIA 2018観測解析 — Aoki — …0観測解析 — SOFIA 2022観測解析
- ハレアカラ 2018観測解析 — Nakagawa & Takami + — ハレアカラ 2022観測解析

**(D)大気鉛直輸送・結合モデル研究**

- モデルへの波動・拡散/化学・鉛直輸送プロセス導入 — **Neary & Kuroda +**
- 平常時・擾乱時の鉛直構造観測量の再現・検証
- 水平メゾスケール観測量の再現・検証
- 火星古環境・太陽系初期想定モデルへ成果反映と、火星大気進化の追跡

**Kuroda / Kamada / Toriumi +**
**Terada / Nakamura / Koyama +**



# Japan-Belgium partnership in 2018-2019

**(0) Organizing & Science meetings**

- Science meetings @Japan May/Oct 2017, Jan/**Feb 2019**
  @Belguim etc. June 2017, **Feb/Sep 2018**

**(1) Groundbased / Airborne observations** – Mars & Venus

- Heterodyne+MAVEN @Belgium June 2017
- ALMA analyses @Japan Nov 2017, **Feb 2019**
- SOFIA analyses @Japan Nov 2017

**(2) Limb retrieval code** *toward 'ExoMars TGO'*

- JACOSPAR@Mars @Belgium **Feb-Mar. 2018**
  @Japan **Feb 2019**

**(3) GCM collaborations** -- Mars & Venus

- Martian GCM @Belgium June 2017
  @Japan **Feb 2019**
- Paleo-Mars GCM with oceans [Kamada et al., submitted]
- Venus GCM with cloud scheme [Kuroda et al., to be submitted]

**(4) Spacecraft analysis** -- Mars & Venus

- MAVEN → VEX / TGO @Belgium etc. **Feb/Oct 2018**, Jan/**Feb 2019**

Closure meeting: as a part of
**'惑星圏シンポジウム' @ 仙台 (18-21 Feb 2019)**
**with Belgian colleagues.**





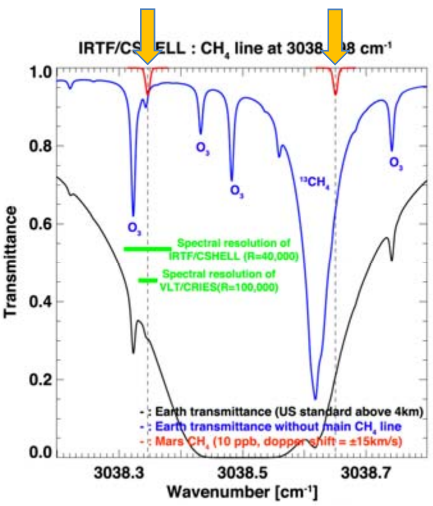
**(1) Lower atmospheric observations** Aoki et al. (invited)

# SOFIA/EXES (NIR spectroscopy from Stratosphere [~15km])

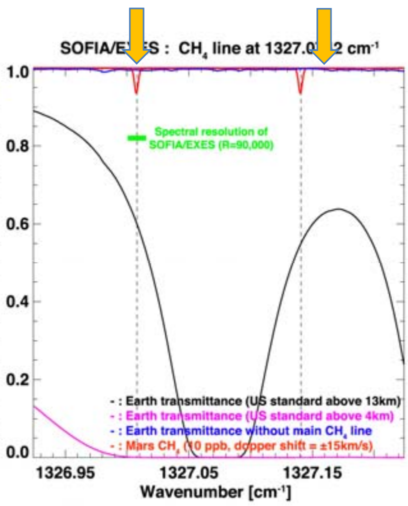
## <$CH_4$ on Mars ??>

- Observations for **$HDO/H_2O$** (PI: *Encrenaz*) and for **$CH_4$** (PI: *Aoki*) executed in **Mar. 2016 (Ls: 123)** + ***Jan 2017 (Ls=305).***
  → Each slit location requires just over **5-min** to detect $CH_4$ at **a several ppb**.

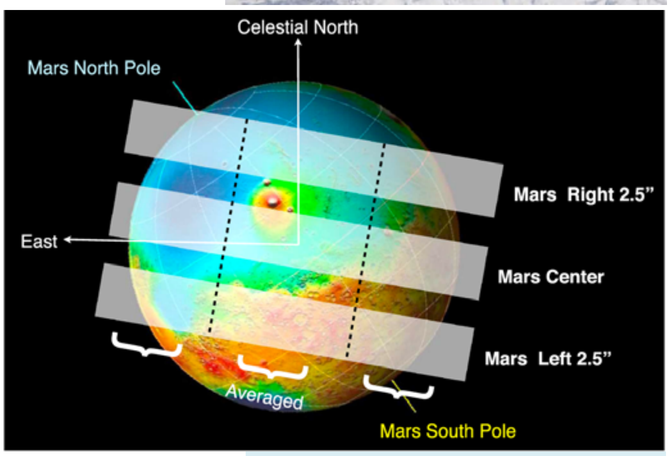
**$CH_4$ by MSL: 0.2-1.0 ppb**




IRTF-3m (Mauna Kea, ~4km)




SOFIA-2.5m (~15km)




Slit positions (Mar 16, 2016)

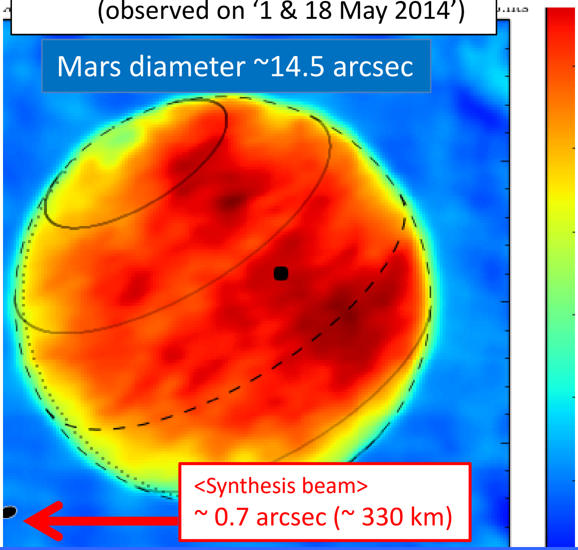
**The first result by ExoMars TGO will be submitted to Nature soon.**

Robert et al. [EPSC2018-811]

ALMA

# First observation of Mars with ALMA (PI: S. Aoki)
## ~ CO & Wind velocity measurements ~

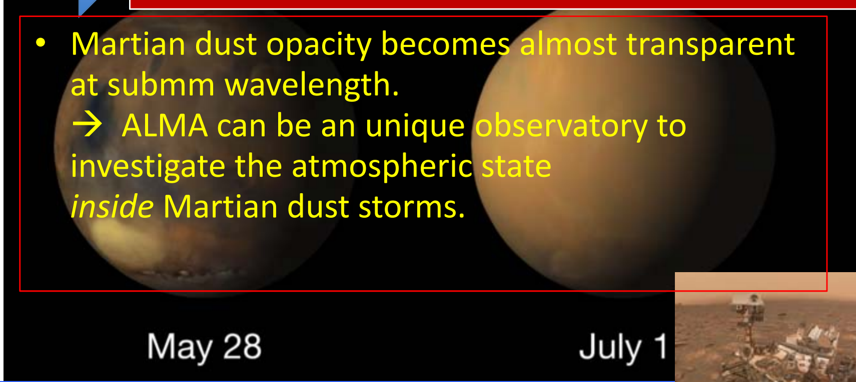

Continuum @ 335 GHz
= Surface temperature map
(observed on '1 & 18 May 2014')



Mars diameter ~14.5 arcsec

<Synthesis beam>
~ 0.7 arcsec (~ 330 km)

2018 Dust Storm was also observed on 29 June !!




- Martian dust opacity becomes almost transparent at submm wavelength.
  → ALMA can be an unique observatory to investigate the atmospheric state *inside* Martian dust storms.

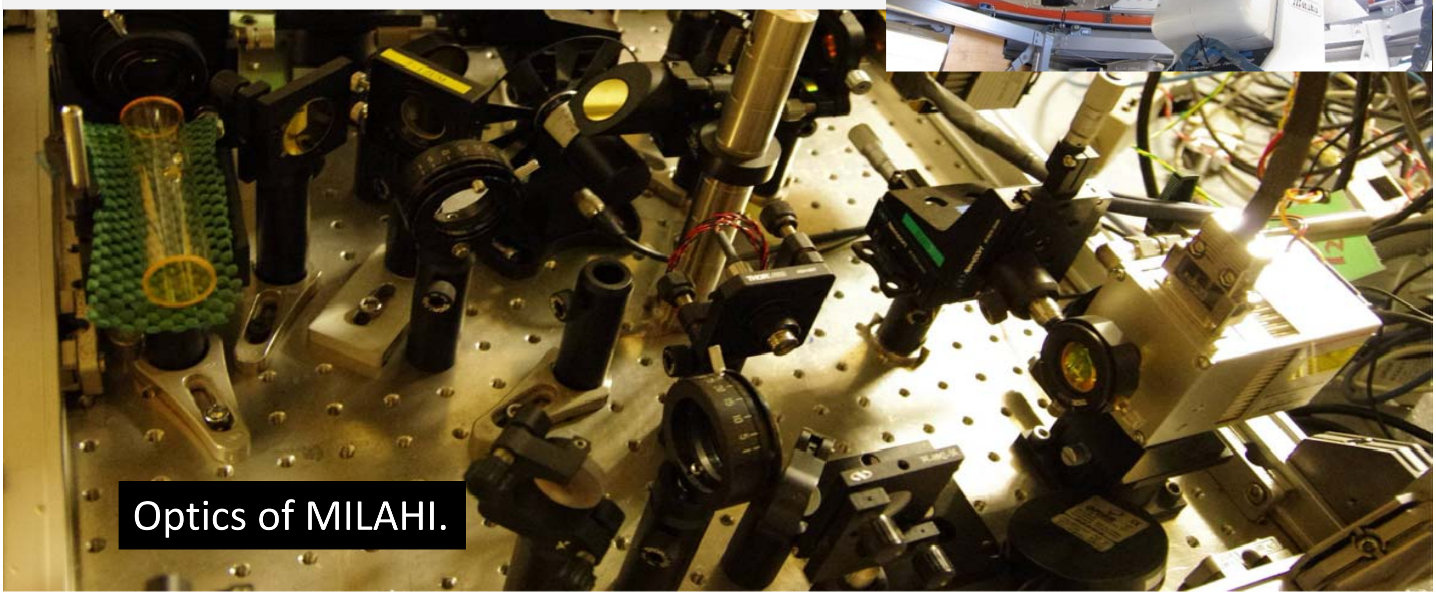
Analyses works are executing by
Aoki + Severine Robert (IASB) with Sagawa (Kyoto Sangyo Univ.).

# Mid-IR Laser Heterodyne Instrument (MILAHI)

- installed at **Tohoku Univ. 60cm @ Haleakala.**
  → **Long observation time** can be applied.
- Spectral Resolution of **$10^{6-7}$ (= 10m/s in velocity)** at **7-12 um**
  → **full resolution** for the narrow trace gases
- Not 'best' spatial resolution (**2.6"** at 7 micron) … still comparable to the SOFIA measurement.

Tohoku Univ. 60cm @ Haleakala

Nakagawa +

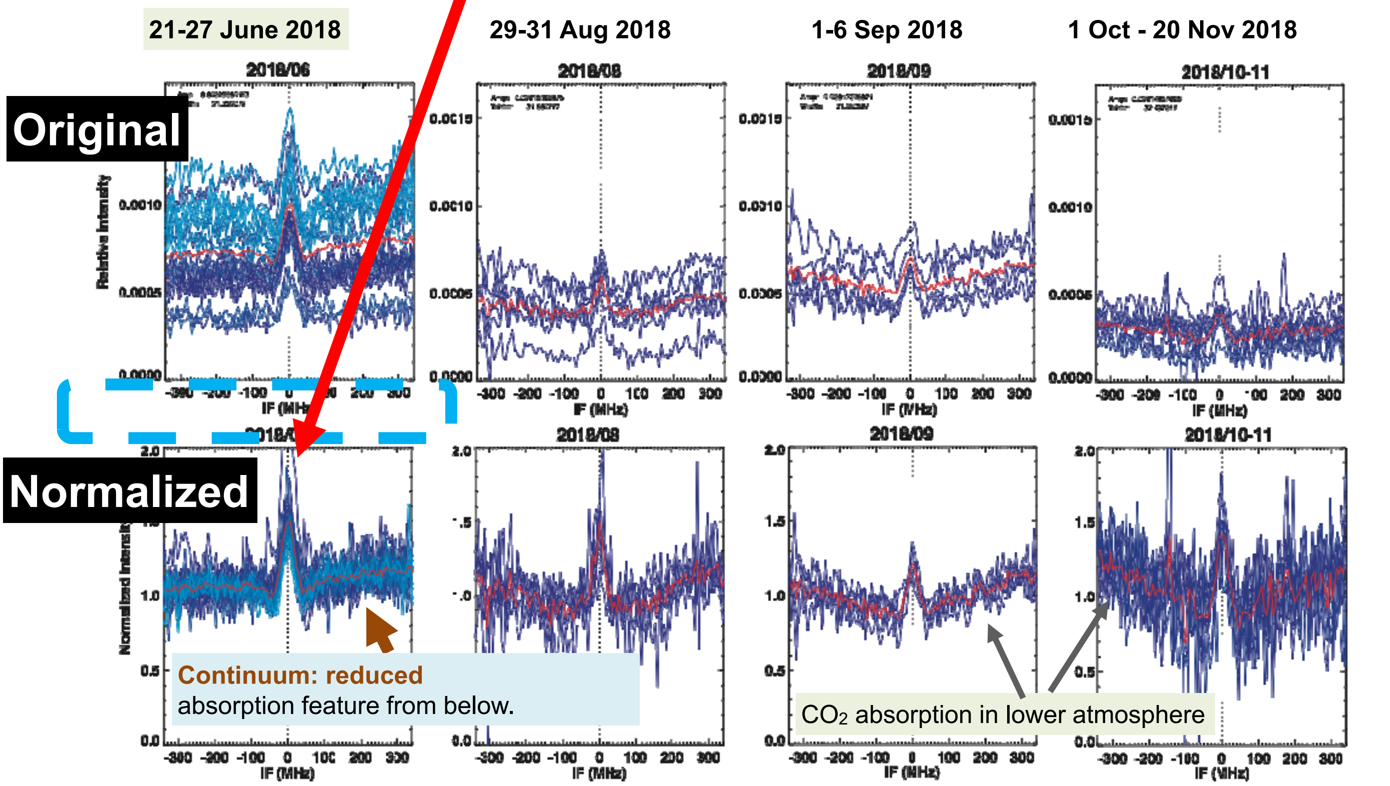


Optics of MILAHI.

# Observed $CO_2$ non-LTE Spectra: a Quick result

- **Remarkable enhancement of the emission line during dust storm.**

Nakagawa +




Temperature & **Wind velocity: now analyzing**

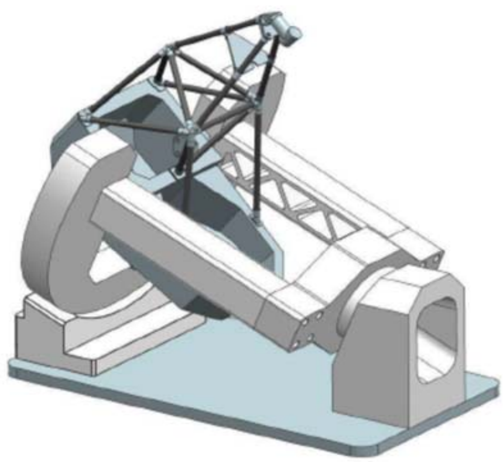
# PLANETS 1.8-m off-axis telescope

https://www.planets.life/

- ✓ Mid-size low-scattering light telescope
- ✓ Continuous monitoring observation of planetary and exoplanetary targets

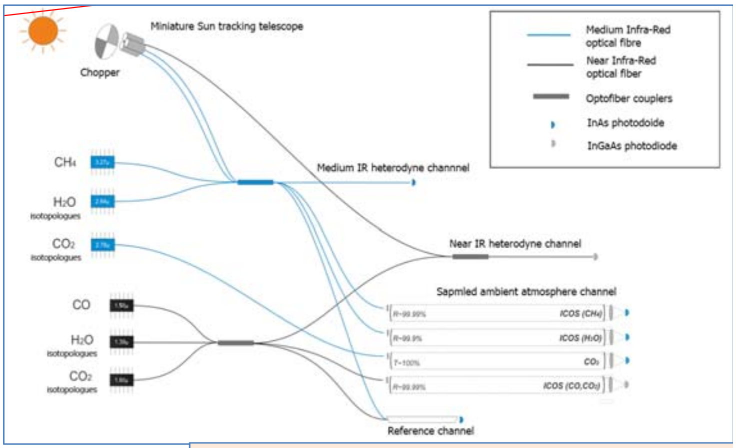
Contribution from us may be enhanced… with Nagoya Univ. Kyoto Univ.

**Sakanoi et al. (poster)**



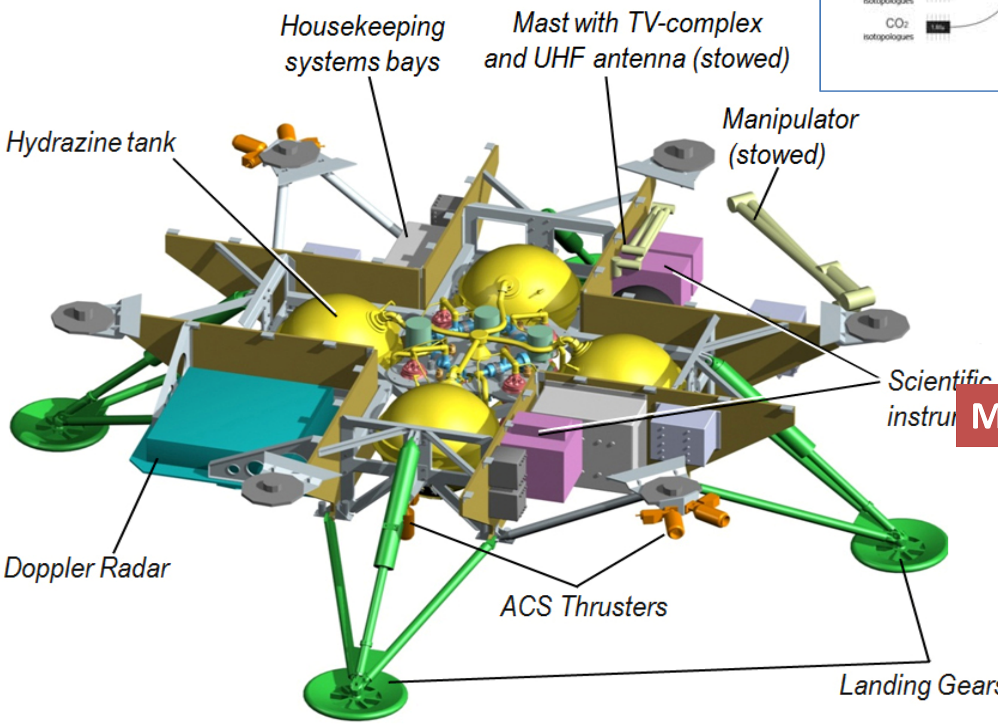
The PLANETS telescope project is promoted and will be operated by the PLANETS foundation consists of Tohoku Univ., IfA/UH, KIS, Brazil, France etc.

# Landing platform: ExoMars 2020

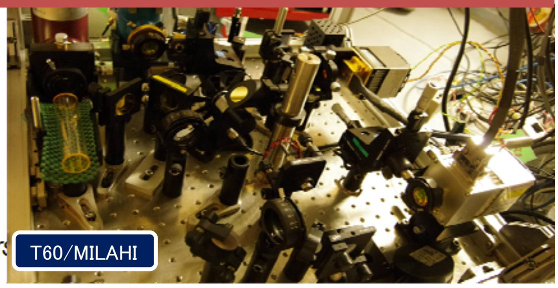



火星着陸機ExoMars EDM搭載赤外レーザーファイバー分光器M-DLSの当初構想図。
実際には機能を落とした簡略設計となったため、まだ日の目を見ていない。
MIPTで開発 [Rodin, private communication]

→ *extracted to Venera-D*



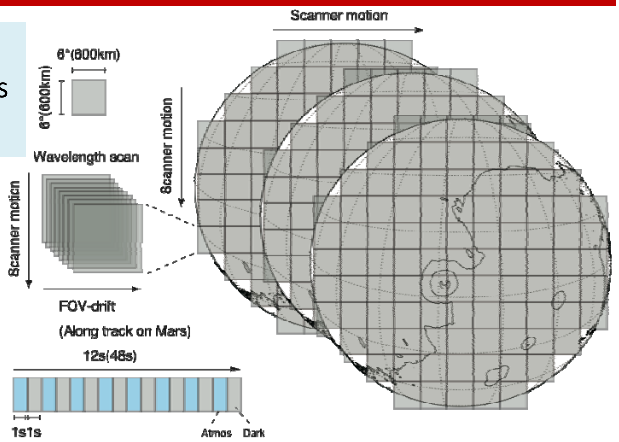

**MIR/NIR-fibers for our Hetrodyne**




## Next of Next: Mars @ JAXA MMX (2024? -): Diurnal variations in Full-disk coverage

*-18-*


[Resolution]
- 2.5 km on Mars
- 1 hour ?




**"Mars – The Cutting Edge Today"**

Trace Gases: $CH_4$, CO, $O_2$, $O_3$, $H_2O$, HDO, $H_2O_2$, etc.
- 3-D spatial: longitude, latitude, & vertical
- 1-D temporal: diurnal, seasonal, & inter-annual)
- High resolution (spectral & spatial)

Orbiters & Rovers
- MGS, MRO, Mars Express, Maven, *ExoMars 2016*
- Curiosity, *ExoMars 2018, Mars 2020*

Ground-based
- Keck, NASA-IRTF, VLT
- ALMA, SOFIA

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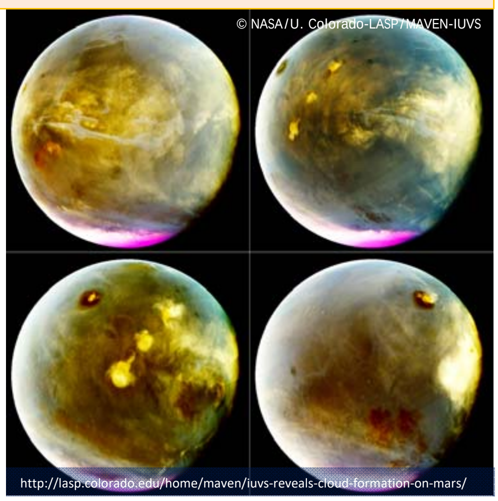
<Current Best> ***6-9 km*** resolution images by ***MAVEN IUVS*** *[7h-interval, July 9-10, 2016]*




→ 「水の行方」に代表される現火星の大気変動、
特に物質・エネルギーの鉛直輸送機構を解明へ。
MMX打上
(2024予定)
2018
2019
2020 – 2021
2022 – 2023
JACOSPAR
MEX
MAVEN
ALMA
SOFIA
T60/MILAHI
(A) 下層大気の鉛直構造観測
JACOSPARの開発・検証
+地表/地下との結合
MEX等のリム観測データの総合解析
TGOの太陽掩蔽・リム観測データの総合解析
ExoMars TGO
対流圏-中間圏
鉛直分布構造観測
(from Orbiters)
(B) 上層大気の鉛直構造観測
MAVEN・粒子観測データの総合解析
MAVEN・紫外観測データの総合解析
Hisakiの全球ダストストーム時紫外観測データの解析
TGO・紫外観測データの総合解析
熱圏-外圏
(C) 全球大気の水平構造観測
ALMA 2018観測解析
ALMA 2020観測解析
ALMA 2022観測解析
SOFIA 2018観測解析
SOFIA 2020観測解析
SOFIA 2022観測解析
ハレアカラ 2018観測解析
ハレアカラ 2020観測解析
ハレアカラ 2022観測解析
水平分布構造観測
(from Earth)
(D)大気鉛直輸送・結合モデル研究
モデルへの波動・拡散/化学・鉛直輸送プロセス導入
平常時・擾乱時の鉛直構造観測量の再現・検証
水平メゾスケール観測量の再現・検証 (MMXへの展開)
火星古環境・太陽系初期想定モデルへ成果反映と、火星大気進化の追跡
数値モデルによる
現・過去火星環境評価